Looking back on 20 years of modelling jet quenching

Korinna Zapp

Lund University

International Workshop "Never at Rest: A Lifetime Inquiry of QGP"

European Research Council
Established by the European Commission

Lund University

MCnet

20 years ago

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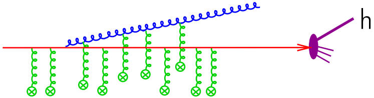

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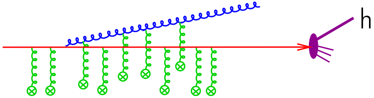
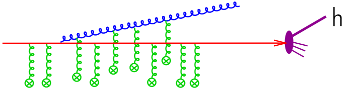


- and in Heidelberg a young physicist finishes her Master and together with her supervisor think about a PhD project.

The conclusion

At the LHC



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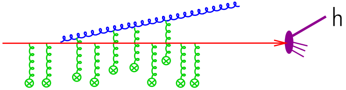
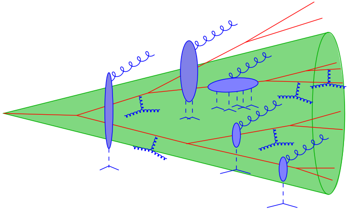
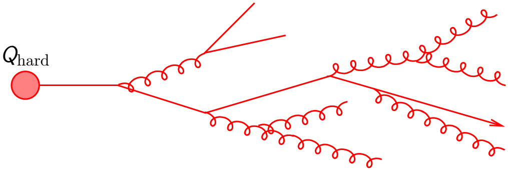


will turn into



⇒ We need a model for this!

Why this is a hard problem



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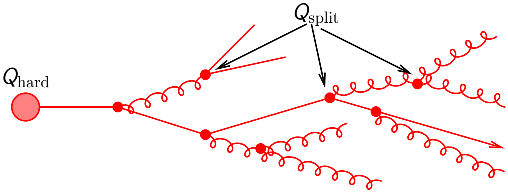

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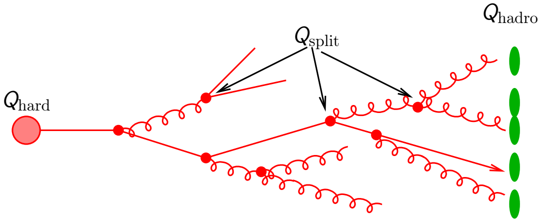

- Q_{hard}: $\mathcal{O}(100\,\mathrm{GeV} - 1\,\mathrm{TeV})$
- Q_{hadro}: $\mathcal{O}(1\,\mathrm{GeV})$
- Q_{split}: $Q_{\mathrm{hard}} > Q_{\mathrm{split}} > Q_{\mathrm{hadro}}$

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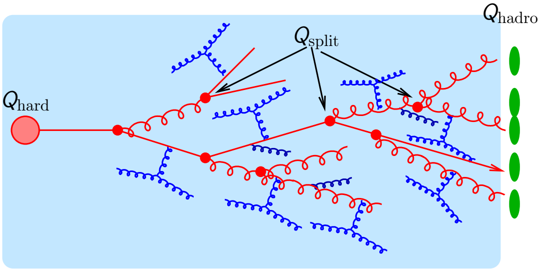

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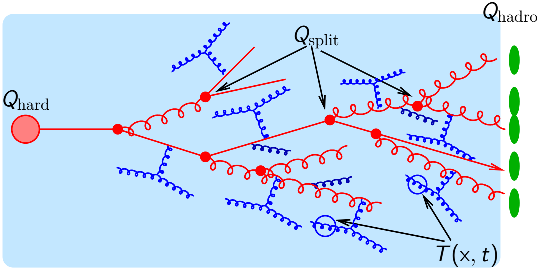

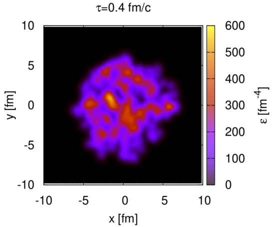

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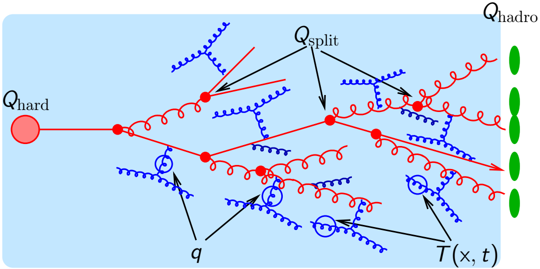

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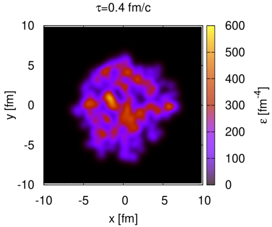
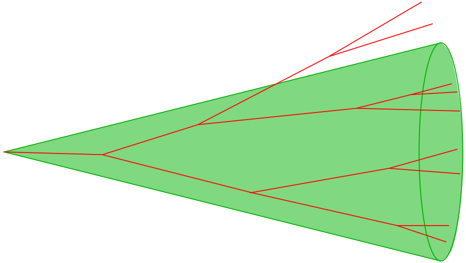


Is it worth the effort?

- jets are a "calibrated" probe: well understood in p+p

fixed order matrix elements + resummation (parton showers)



- jet quenching allows to observe *process* of equilibration

soft observables see *result* of equilibration

- jets carry information about spacial and temporal structure of medium
- jets give access to scale dependence of medium properties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NEIN - NICHT
ZUR PHYSIK


12
NEIN - NICHT
ZUR PHYSIK

JEWEL: Basic idea and assumptions

Starting point

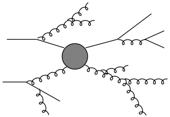
- complexity of problem asks for Monte Carlo event generator
- consistent dynamical model of jet evolution in medium
- anchored in analytical understanding of pQCD

Assumptions

1. medium as seen by jet: collection of quasi-free partons
2. use infra-red continued perturbation theory to describe all jet-medium interactions
3. formation times govern the interplay of different sources of radiation
4. use results from eikonal limit to include LPM-effect

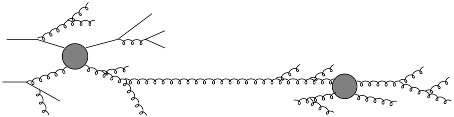
Zapp, Krauss & Wiedemann, JHEP 1303 (2013) 080

JEWEL in a nutshell



- jet production in initial N+N collisions: ME+PS

JEWEL in a nutshell



- jet production in initial N+N collisions: ME+PS
- re-scattering: ME+PS
  - generates elastic & inelastic processes
  - with leading log correct relative rates
  - general kinematics

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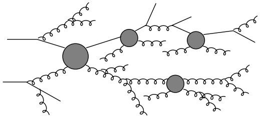

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- emission with shortest formation time is realised
  - all emissions (vacuum & medium induced) treated equally
  - hard structures remain unperturbed

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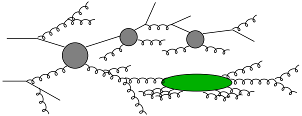
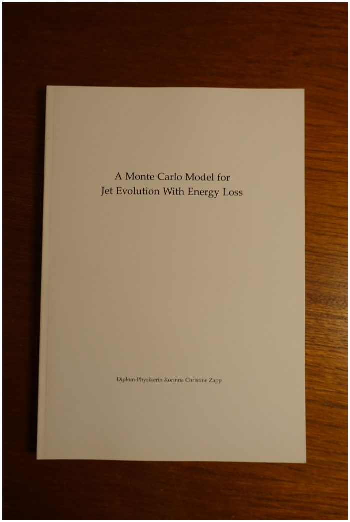


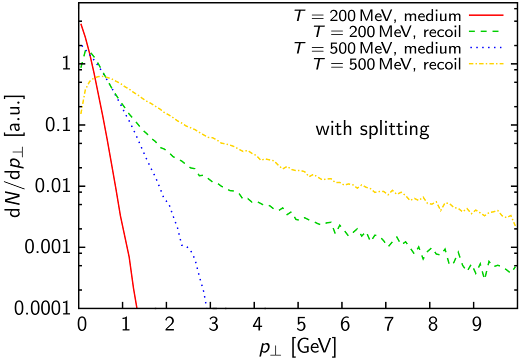
- jet production in initial N+N collisions: ME+PS
- re-scattering: ME+PS
  - generates elastic & inelastic processes
  - with leading log correct relative rates
  - general kinematics
- emission with shortest formation time is realised
  - all emissions (vacuum & medium induced) treated equally
  - hard structures remain unperturbed
- LPM interference
  - also governed by formation times
  - without kinematic restrictions

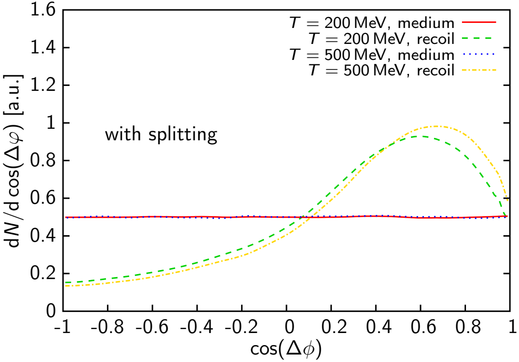
Zapp, Stachel, Wiedemann, JHEP **1107** (2011) 118

Three years later. . .



Where does the 'lost' energy go?

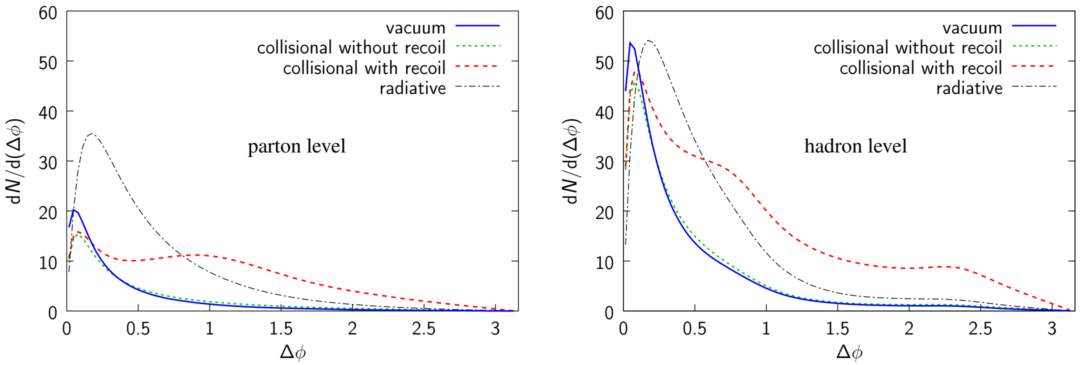




Zapp, Ingelman, Rathsman, Stachel, Wiedemann, Eur. Phys. J. C **60**, 617 (2009)

- medium response before there was medium response
- relativ angle almost independent of temperature

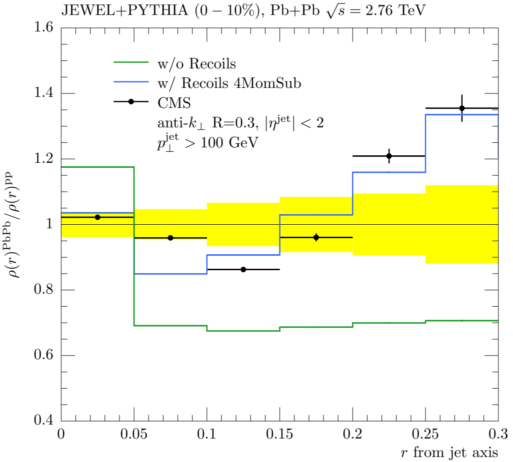
Where does the ‘lost’ energy go?



K. Zapp, PhD thesis

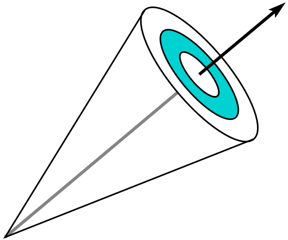
- enhancement of fragments around jets out to large angles

Some years later: the jet profile is measured



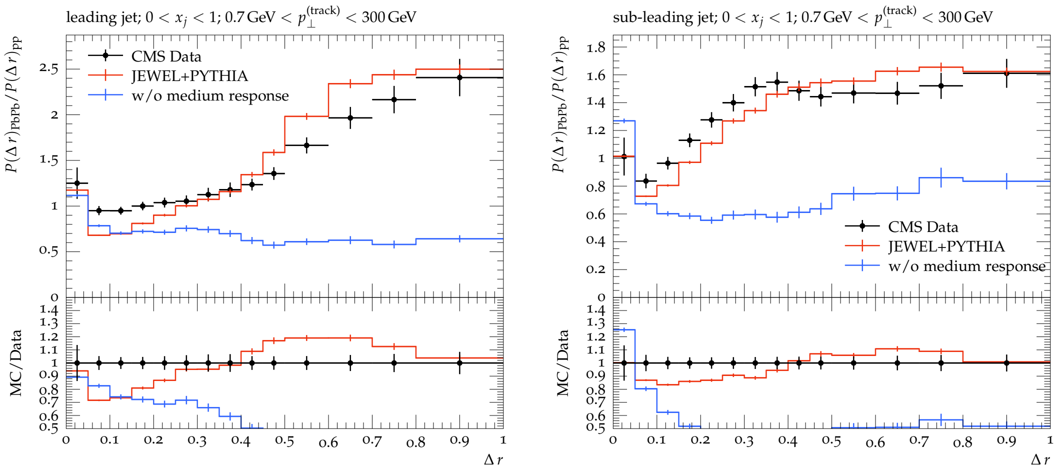
CMS, Phys. Lett. B **730** (2014) 243

Kunnawalkam Elayavalli, Zapp, JHEP **1707** (2017) 141



- fraction of jet $p_\perp$ contained in annulus at distance r from jet axis

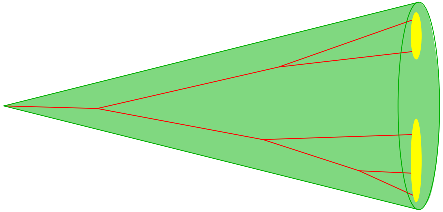
Jet–hadron correlations today



CMS, JHEP 05 (2021), 116 [arXiv:2101.04720]

Identifying hard structures inside jets: SoftDrop

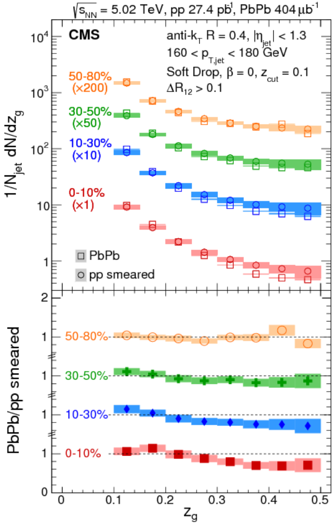
M. Dasgupta, A. Fregoso, S. Marzani, G. P. Salam, JHEP **1309** (2013) 029
A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler, JHEP **1405** (2014) 146

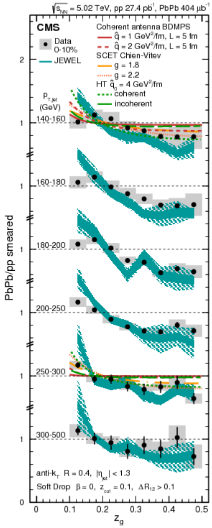


- SoftDrop procedure: identifies hard 2-prong structure inside a jet
- removes soft large angle particles mostly coming from background

- walk backwards through the jet clustering sequence
- stop when momentum sharing $z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} > z_{\text{cut}}$
- at LO: $p(z_g) \propto P(z_g) + P(1 - z_g) \rightarrow$ proportional to splitting function

Measuring the splitting function?

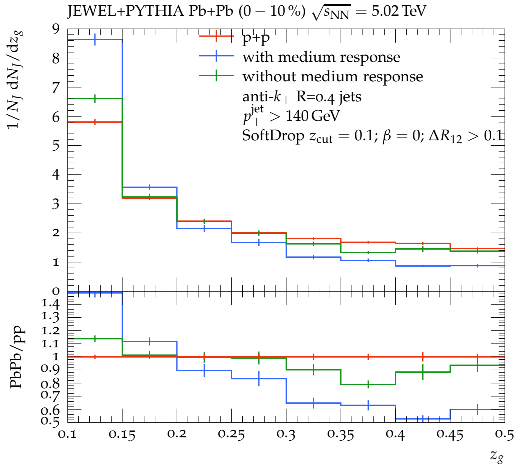


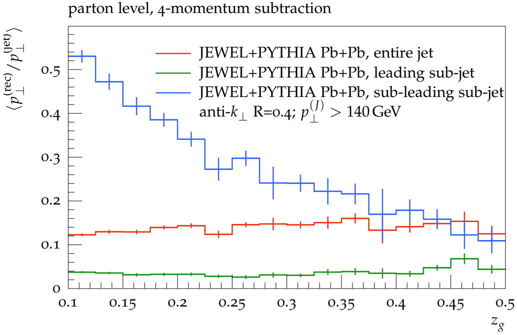


CMS, Phys. Rev. Lett. 120 (2018) no.14, 142302

- suppression of symmetric splittings
- JEWEL describes this nicely
- but without a modified splitting function!

What is going on here?

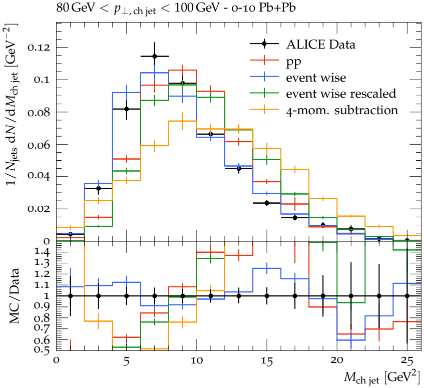




- medium response promotes sub-leading sub-jets above z_{cut}

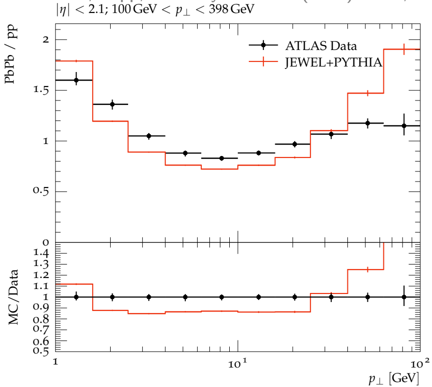
Milhano, Wiedemann, Zapp, Phys. Lett. B **779** (2018), 409-413

Improving the subtraction procedure



ALICE, Phys. Lett. B 776 (2018), 249-264

Milhano, Zapp, Eur. Phys. J. C 82 (2022) no.11, 1010 [2207.14814]



ATLAS, Eur. Phys. J. C 77 (2017) no.6, 379

- thermal momentum of recoils part of background → has to be subtracted
- more robust and flexible procedure implemented

allows to calculate IRC-unsafe observables

Looking ahead

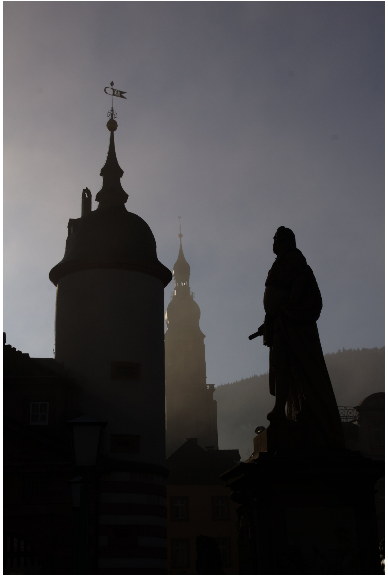
Open questions

- To what extent is medium response thermalised?
- How much of the large Δr enhancement is due to medium induced radiation?
- Is the wake hydrodynamic response or momentum conservation?

Other jetty questions

- When and how is colour coherence lost?
- At which scale are quasiparticles in the QGP resolved?
- What is going on in small systems?

$\rightarrow$ no answer without understanding of medium response



Thank you!

Medium's response to energy deposited by jets

- common assumption: immediate thermalisation
- JEWEL: three options

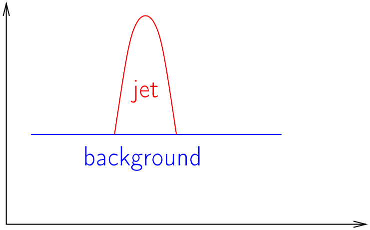
1. ignore recoiling thermal partons
2. extract source term for hydrodynamic description of medium

Flörchinger, Zapp, EPJC **74** (2014) no. 12, 3189

3. include recoiling partons
   - recoiling partons becomes colour neighbour of hard parton
   - recoiling partons do not re-interact
   - have so subtract thermal component of recoil momentum

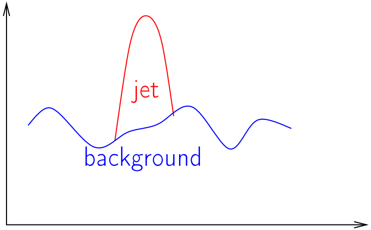
other limiting case

Medium response: practical considerations



- ideal situation: flat background – can be subtracted

Medium response: practical considerations



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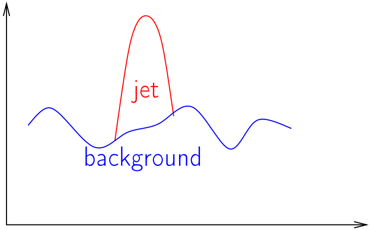
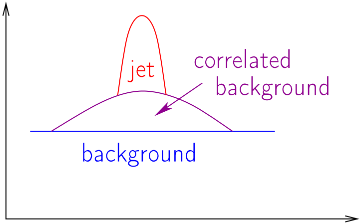
- more realistic: fluctuating background – can be subtracted on average, have to unfold

Medium response: practical considerations





- ideal situation: flat background – can be subtracted
- more realistic: fluctuating background – can be subtracted on average, have to unfold
- adding medium response: correlated background
  - part of the background is correlated with jet $\rightarrow$ medium response
  - activity above uncorrelated background
  - correlated background cannot and should not be subtracted

Medium response: practical considerations

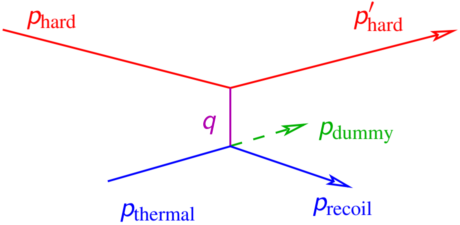
- ideal situation: flat background – can be subtracted
- more realistic: fluctuating background – can be subtracted on average, have to unfold
- adding medium response: correlated background
  - part of the background is correlated with jet → medium response
  - activity above uncorrelated background
  - correlated background cannot and should not be subtracted
- finally: also fluctuations in correlated part of background matter

Background subtraction in A+A – general considerations

- experimentally: background subtraction absolutely necessary
- what would be there without the jet should be subtracted
- correlated background component should stay
- for fair theory–data comparison:
  procedure on theory side as close to experimental one as possible
- but: JEWEL only simulates jets, no full events
- have to implement procedure that equals experimental one in spirit
- keep the recoils, but subtract incoming thermal momenta

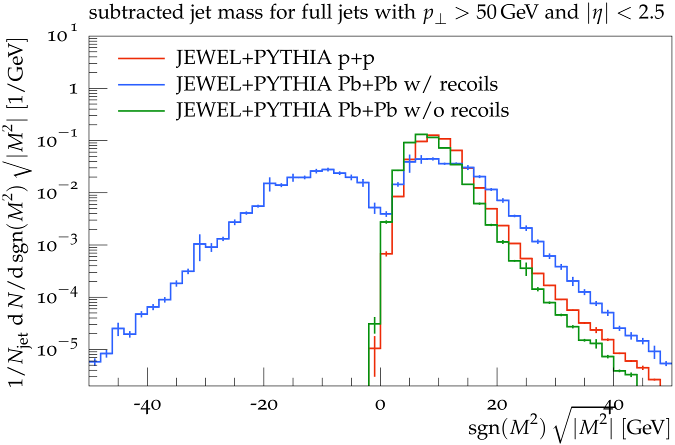
Background subtraction in JEWEL

- old method: 4-momentum subtraction

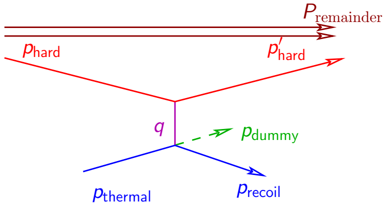


- for each thermal momentum add dummy momentum with very small energy to event
- for each dummy in jet subtract corresponding thermal 4-momentum from jet 4-momentum
- works fine for IRC safe observables
- for jet sub-structure: may have to do it iteratively
- one observable problematic: jet mass

4-momentum subtraction: jet mass



4-momentum subtraction: jet mass



$$P_{\text{jet}} = P_{\text{remainder}} + p'_{\text{hard}} + p_{\text{recoil}} - p_{\text{thermal}} = P_{\text{remainder}} + p'_{\text{hard}} - q$$

if p'_{hard} ends up outside the jet cone — not all that unlikely

$$P_{\text{jet}} = P_{\text{remainder}} + p'_{\text{hard}} - q$$

$$M_{\text{jet}}^2 = (P_{\text{remainder}} - q)^2 = M_{\text{remainder}}^2 + \hat{t} - 2qP_{\text{remainder}}$$

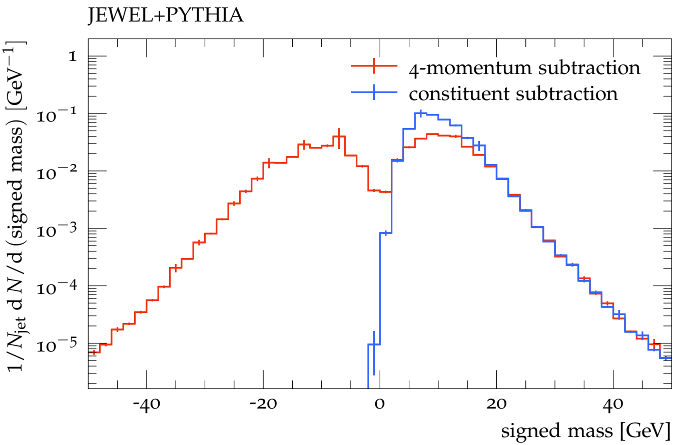
A better choice: constituent subtraction

Berta, Spousta, Miller, Leitner, JHEP **06** (2014), 092 [arXiv:1403.3108]

The algorithm

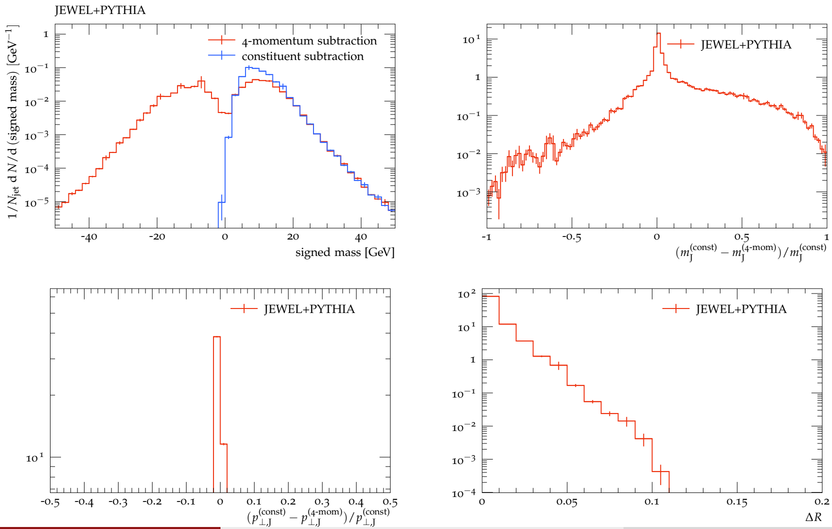
1. write all 4-momenta as $p = ((m_\delta + p_\perp)\cosh y,\ p_\perp \cos\phi,\ p_\perp \sin\phi,\ (m_\delta + p_\perp)\sinh y)$
2. form all pairs of a particle momentum and a thermal momentum, sort by ΔR
3. go through ordered list of pairs, for each pair:
   - subtract smaller from larger $p_\perp$, set smaller $p_\perp$ to zero
   - subtract smaller from larger m_δ, set smaller m_δ to zero
4. remove all momenta with zero $p_\perp$

Constituent subtraction: jet mass



Milhano, Zapp, Eur. Phys. J. C 82 (2022) no.11, 1010

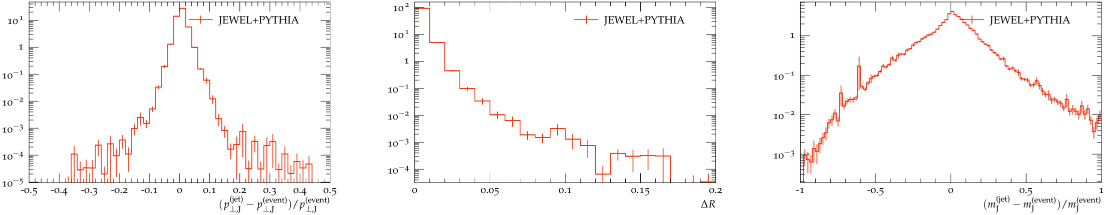
Constituent subtraction: jet mass



Milhano, Zapp, Eur. Phys. J. C 82 (2022) no.11, 1010

Constituent subtraction: Some remarks

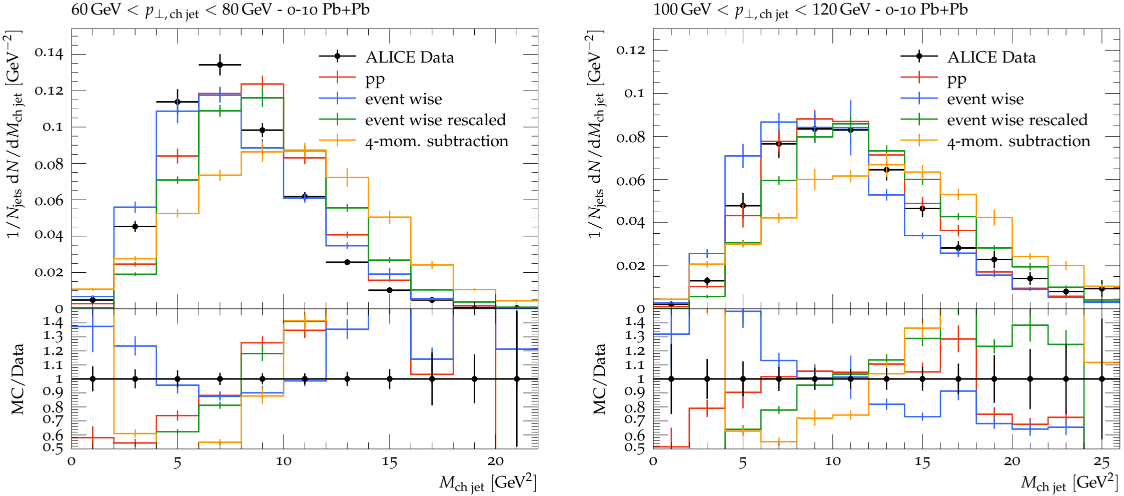
- squared mass remains positive by construction
- other observables don't change w.r.t. 4-momentum subtraction
- two possible workflows:
  1. first reconstruct jets, then subtract jet-wise
  2. first subtract event, then reconstruct jets



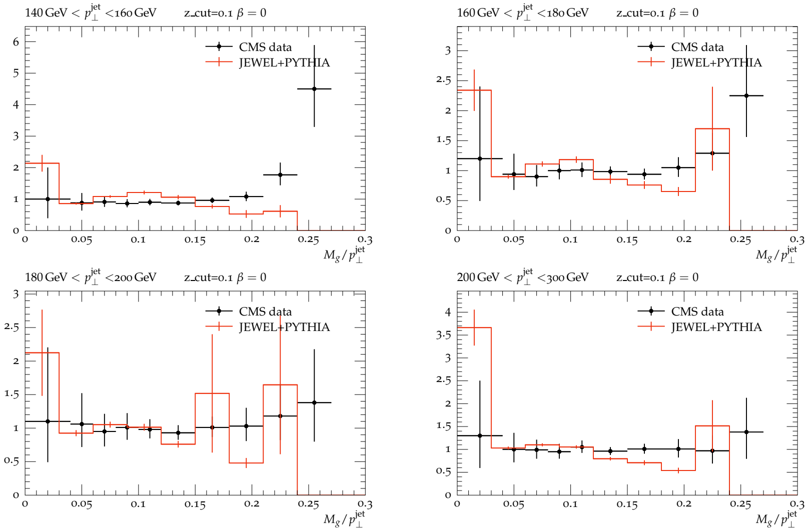
- inside jets all thermal momenta disappear
- can keep track of hadron flavour inside jets
- can calculate IRC unsafe observables

Constituent subtraction: jet mass

ALICE, Phys. Lett. B **776** (2018), 249-264 [arXiv:1702.00804]

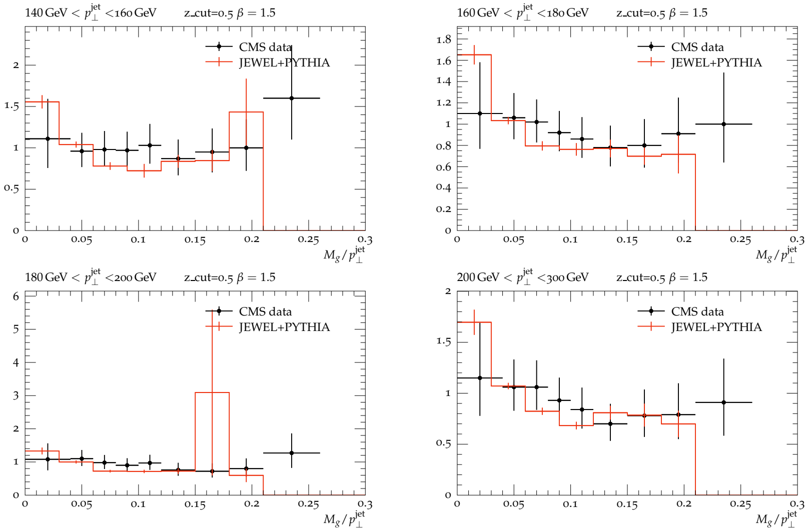


Constituent subtraction: groomed jet mass



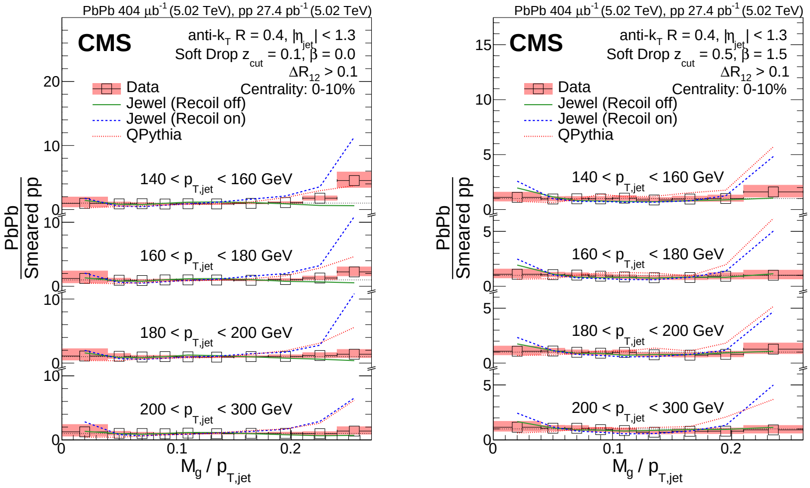
CMS, JHEP 10 (2018), 161 [arXiv:1805.05145]

Constituent subtraction: groomed jet mass



CMS, JHEP 10 (2018), 161 [arXiv:1805.05145]

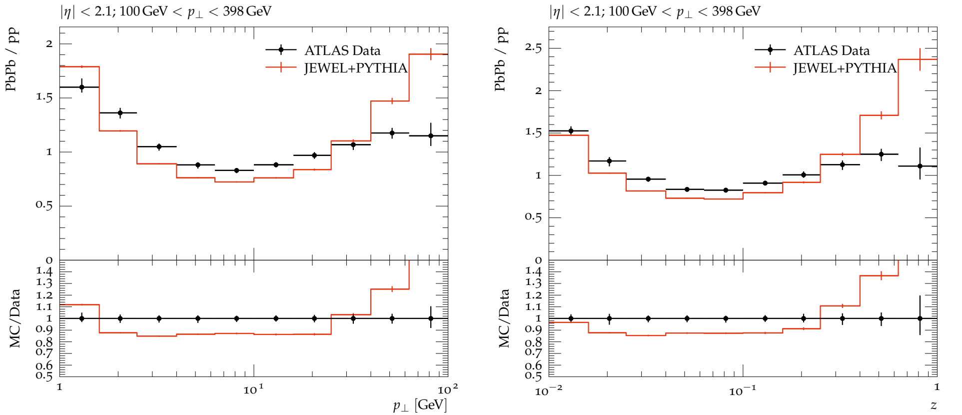
Constituent subtraction: groomed jet mass



CMS, JHEP 10 (2018), 161 [arXiv:1805.05145]

Constituent subtraction: jet fragmentation function

ATLAS, Eur. Phys. J. C **77** (2017) no.6, 379 [arXiv:1702.00674]



- jet collimation effect too strong, but soft part not bad